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Simulations of a Maxwellian Plasma using an Electron Beam Ion Trap

D. W. Savin,[1] B. Beck,[2] P. Beiersdorfer,[2] S. M. Kahn,[1] G. V. Brown,[2] M. F. Gu,[1] D. A. Liedahl[2] and J. H. Scofield[2]

[1] Department of Physics and Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
[2] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

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Abstract

Using the Lawrence-Livermore electron beam ion trap (LLNL-EBIT), we produce a quasi-Maxwellian plasma by sweeping the energy of the nearly monoenergetic beam so the time spent an any energy is proportional to the Maxwell-Boltzmann probability at that energy. To verify the accuracy of the quasi-Maxwellian, we measure line emission due to dielectronic recombination (DR) and electron impact excitation (EIE) of Mg^{10+} and Ne^{8+}, for a range of simulated temperatures. The ratio of DR to EIE lines in heliumlike ions is a well understood temperature diagnostic. The spectroscopically inferred temperatures are in excellent agreement with the simulated temperatures.

1. Introduction

The LLNL-EBIT [1, 2] offers a number of advantages over standard plasma sources for studying Maxwellian plasmas. EBIT is essentially driven by a Maxwellian electron distribution at a single temperature T_e; a wide range of T_e can be simulated; density effects are generally unimportant; the plasma is optically thin; and T_e is essentially constant along the line of sight. Another advantage is the ability to create ions of a given charge state and then study them in a Maxwellian plasma under non-equilibrium conditions.

We measure line emission due to DR and EIE of Mg^{10+} and Ne^{8+} in order to determine the accuracy of the simulated Maxwell-Boltzmann distribution. Heliumlike ions are commonly used to measure T_e of a plasma by forming the ratio of DR to EIE lines [3, 4]. Here we observe (using the notation of Gabriel [5]) the DR lines *a*, *b*, *c*, *d*, *j*, *k*, *l*, *q*, and *r* which are unresolved by our spectrometers, and the EIE line *w* plus DR satellite lines which blend with *w*. We refer to these blended features as *j* and *w*.

2. Experimental arrangement

EBIT uses a nearly monoenergetic beam of electrons to produce and trap ions. To simulate a Maxwell-Boltzmann electron energy distribution, we sweep the beam energy E in time so the time-averaged energy distribution closely approximates a Maxwell-Boltzmann distribution. E is swept between $E_{\min}$ and $E_{\max}$ with a typical period of 5 ms. The values used for $E_{\min}$ and $E_{\max}$ depend on the T_e being simulated. In general $E_{\min} \gtrsim 0.2$ keV because the beam is poorly behaved below this energy, and $E_{\max} \lesssim 15.0$ keV because at higher energies voltage breakdowns begin to occur inside EBIT. Many of the collision processes we are interested in studying occur for $E > 0.2$ keV; and the simulated T_e (typically $\lesssim 2.0$ keV) have an insignificant population of electrons for $E \gtrsim E_{\max} \sim 5 - 6\ k_B T_e$ keV. The limits $E_{\min}$ and $E_{\max}$ are not expected to affect strongly the line emission of interest.

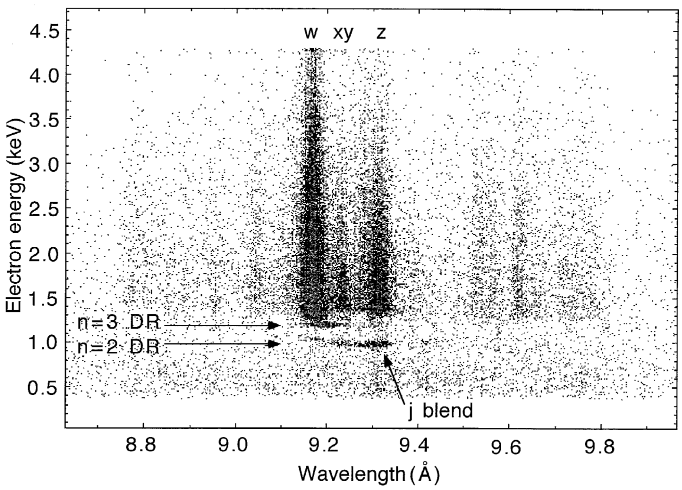

Fig. 1. Scatter plot of photon λ versus E for a Maxwellian simulation of $T_e = 0.7$ keV. The vertical features above $E \sim 1.35$ keV are due to EIE of Mg^{10+}, and are (using the notation of Gabriel [4]) *w*, *x* and *y* which are blended, and *z*. The features at $E \sim 0.98$ are due to DR into the $n = 2$ level of Mg^{9+}. The features at $E \sim 1.2$ keV are DR into the $n = 3$ level. The low energy tail which maps smoothly onto *w* is due to $n \geq 4$ DR.

The electron density is kept nearly constant during the E sweep to maintain an electron-ion overlap independent of E. This insures all electron-ion collision processes for a given charge state have the same geometric overlap factor, just as they would in a true Maxwellian plasma.

For the present results we use flat crystal spectrometers [6, 7] to record the resulting X-ray emission. The photon energy, electron beam energy, and time of each event are recorded using an "event-mode" data acquisition scheme [8]. Raw data from a typical Maxwellian simulation are shown as a scatter plot of photon wavelength versus beam energy in Fig. 1.

3. Results and Discussion

Using data such as shown in Fig. 1, we extract the intensities of *j* and *w* for a number of simulated T_e. We select against contributions to *j* due to DR and EIE of the heliumlike ions and EIE and innershell ionization of the lithiumlike ions using the known beam energy for every detected photon. Radiative recombination (RR) onto hydrogenic ions can contribute to *w* and also at energies below threshold to *z* which blends with *j*. Observations of hydrogenic and heliumlike lines simultaneous with those of *j* and *w* are used to determine the H-like/He-like abundances. We estimate the RR contributions to be insignificant. Charge transfer (CT) of

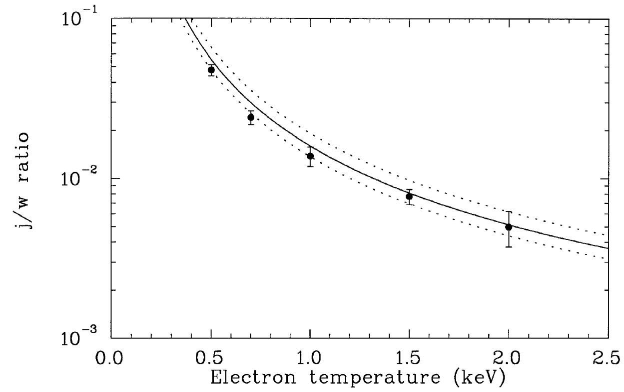

Fig. 2. Experimental magnesium j/w ratio versus T_e assuming a perfect Maxwellian simulation. The solid curve is the best guess theoretical ratio. The rate coefficient for w is from Zhang and Sampson [9]. The rate coefficients for the DR lines are from Steenman-Clark *et al.* [10] and Faucher *et al.* [11]. The dotted curves represent the range of theoretical ratios taking into account the HULLAC [12, 13] and Faucher *et al.* [11] calculations of w and the DR calculations of Vainshtein and Safronova [14] and Chen [15].

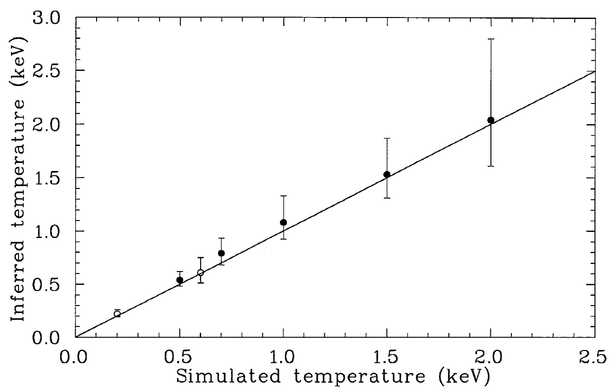

Fig. 3. Inferred T_e versus simulated T_e for magnesium (filled circles) and neon (open circles) using the measured and theoretical j/w ratios. The inferred T_e uses the best guess theoretical ratios. The error bars represent a combination of the experimental error bars and the range of theoretical ratios.

hydrogenic ions with background gas in EBIT can also produce w and z. The CT contributions are subtracted out using data at energies where DR and EIE are insignificant.

The measured j/w ratios for magnesium are plotted in Fig. 2 with their 1σ total experimental error bars. Various theoretical ratios are also plotted. Using theory we infer T_e and in Fig. 3 plot these results versus the simulated T_e. The inferred T_e are in excellent agreement with those simulated.

4. Conclusion

Using magnesium and neon we have tested our ability to simulate a Maxwell-Boltzmann distribution from the energy of the Ne^{8+} $n = 2$ DR resonances at ~ 0.68 keV to ~ 10.6 keV. Work is in underway to repeat these tests using Ar^{16+} which will allow us to test the electron distribution at higher energies.

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